SWAS-107

SUBMILLIMETER WAVE ASTRONOMY SATELLITE

CONCEPTUAL DESIGN REVIEW

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GODDARD SPACE FLIGHT CENTER

Smithsonian Astrophysical Observatory
Ames Research Center
Ball Aerospace Systems Group
Millitech Corporation
National Air and Space Musuem
University of California at Berkeley
University of Cologne
University of Massachusetts at Amherst

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Ball Aerospace Systems Group

Smithsonian Astrophysical Observatory

Overview

Jim Sears

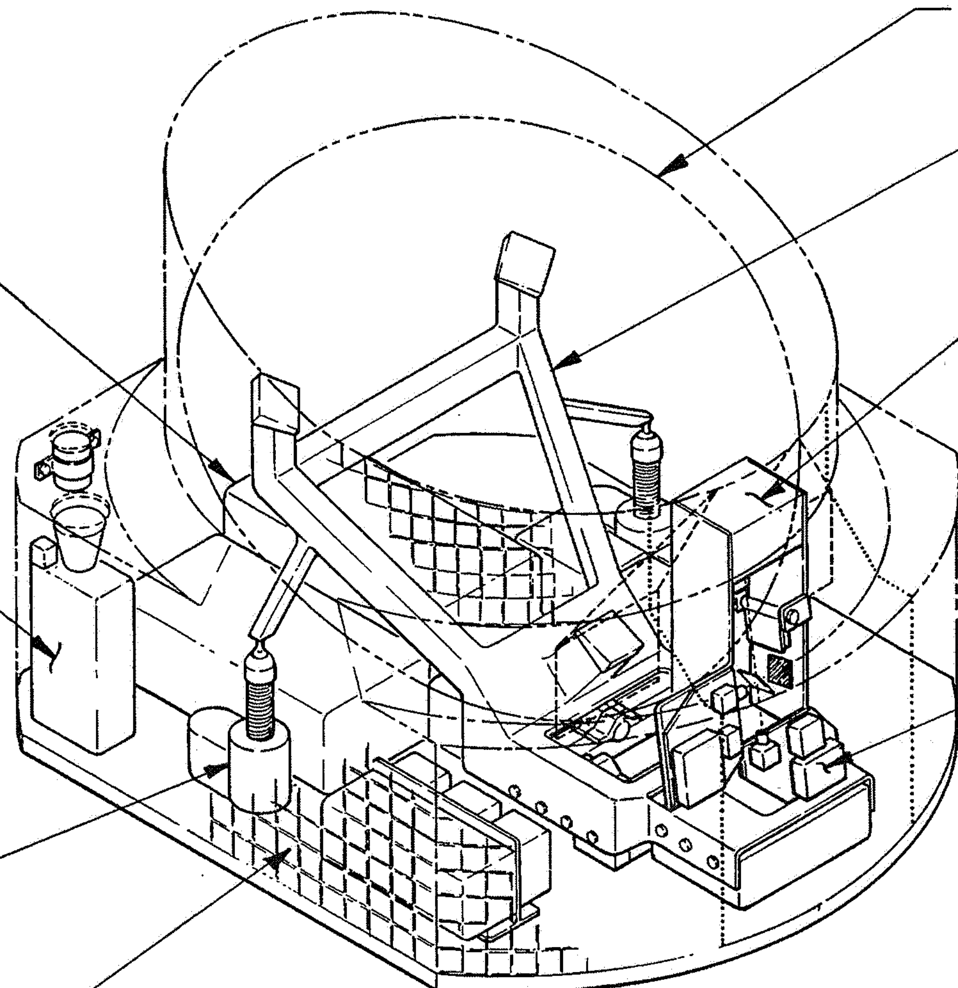
The SWAS instrument consists of the moving telescope assembly, the interface baseplate assembly, and the thermal control housing. The moving telescope structure holds the primary mirror, secondary mirror, and receiver front end in precise alignment. This structure also carries the receiver cold plate radiators, which view cold space both directly and through reflection off the primary mirror.

The moving telescope assembly attaches to the interface baseplate with an open pivot frame through which flex leads from the receiver front end also pass. Two flexure-mounted linear actuators tilt the moving telescope assembly up to ±3 deg in two axes. The interface plate serves as a mounting for these actuators as well as the acousto-optic spectrometer, the instrument control electronics, the star tracker, and the balance of the receiver components.

The thermal control housing attaches to the interface baseplate around its edge. The top cylindrical part of this housing serves to shade the receiver cold plate radiators from Sun and Earth influence. The bottom "D" shaped portion of the housing is thermally isolated from the top and forms the electronics radiator. Heat is conducted from the interface baseplate into this lower portion of the shell. The radiator geometry and conduction paths create a very stable thermal environment in the center of the interface baseplate where the AOS and receiver IF amplifiers are heat sinked. The outer surface of the thermal control housing is covered with fused silica second surface mirrors that reflect visible light and radiate infrared energy.

The instrument is mounted to the spacecraft through four thermally-isolating titanium flexures on the underside of the interface baseplate.

THE SWAS CONCEPT PACKAGES A POWERFUL SCIENCE INSTRUMENT INTO THE SCOUT AND SPACECRAFT ENVELOPE



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The design configuration has satisfied all the packaging and resource allocation requirements of the Scout launch vehicle without compromising the mission science capabilities. These capabilities are in fact increased relative to the Science Requirements Document by increasing the aperture to 55 by 71 cm, which will reduce the time required to map point sources and increase the spatial resolution in extended sources. Increasing the nod capability to ± 3 deg will improve the efficiency of locating and using reference positions. The reliability of the mission has been enhanced over previous concepts by eliminating the requirement for sunshade deployment and launch lock mechanisms.

COMPLETED SWAS CONCEPT POINTS TO AN EXCELLENT INSTRUMENT

- Science objectives fully supported by instrument capabilities
  - Largest telescope aperture for envelope (55x71 cm)
  - Versatile nodding ability
  - Cooled receiver – stable thermal environment
- Design has been configured from the ground up for low weight and power requirements
- Design accommodates desired spacecraft structural concept and nonarticulated solar panels

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The concept definition phase has resulted in baseline instrument characteristics that will serve as the foundation for future definition and design activities.

BASELINE SWAS INSTRUMENT CHARACTERISTICS ARE ESTABLISHED

- Mechanical interface to spacecraft through cruciform structure mounting points (access direction is TBD)
- Electrical interface with spacecraft is 28 V and 1773 fiber optic bus only (except thermistors and attitude control system sensors)
- Moving telescope has ±3 deg commandable nod
- Nondeployed, fixed sunshade (subject to final analysis confirmation)
- 57.3 W power, 44.2 kg weight (zero pad estimate)
- *75 deg Sun, 35 deg Earth avoidance angles* (fixed solar panels accommodated)

Ball Aerospace is fully experienced in designing science instruments for the low Earth orbital space environment. No unique difficulties are expected with the SWAS instrument.

FUNDAMENTAL INSTRUMENT REQUIREMENTS FORM THE SWAS DESIGN BOUNDARIES

- Scout launch
  - Limited size envelope within launch shroud
  - Limited weight and power
  - Stability through launch vibration
  - Interface with spacecraft structure

- Low Earth orbit environment
  - Changing thermal environment during 90-min orbit
  - Atomic oxygen
  - Outgassing condensation
  - Radiation (particularly if nonequatorial orbit is chosen)
  - 2-year life (cross-section area, Sun activity, reliability)

The mission science requirements have driven the design of the instrument and the various concept trade-offs. The major challenges have been cooling the front end and providing the nod ability. All science requirements have been met or exceeded in the baseline design.

SCIENCE DERIVED INSTRUMENT REQUIREMENTS DRIVE THE DESIGN TRADE-OFFS

- Antenna
  - High efficiency, high accuracy
  - Maximum aperture, 4 arc-min beamwidth
  - Nod ability
  - Minimization of baseline ripple
  - Calibration source/flip mirror

- Receiver
  - Cooled front end (exact capability under study)
  - Mechanical stability
  - Thermal stability (0.05 °C/min)

- Acousto-optic spectrometer
  - Mechanical stability
  - Thermal stability (0.2 °C/min)

Several instrument design issues were recognized early on as both challenging and fundamental to the SWAS instrument. Specific studies were formed to address the system performance modeling, nodding method, and sunshade design. This presentation summarizes the results of these specific focuses as well as the other issues that were encountered during the baseline design.

CONCEPT STUDIES AND PERFORMANCE MODEL HAVE EVOLVED SWAS TO PRESENT CONCEPT

- Performance model targeted desired aperture size and cooling goals
- Nodding study established moving telescope concept
- Sunshade study resulted in nondeployed concept, as well as electronics cooling concept
- Performance model will continue to monitor operational performance as design matures

The SWAS performance model will be used as a tool for doing system-level analysis and trade studies. For example, the effect on system sensitivity of trading off primary mirror configuration and passive radiator effectiveness can be evaluated with the performance model. In addition, the model will stimulate a better understanding of the engineering requirements because the effect of various design requirements can be immediately reflected in the system performance. Lastly, the model will provide a theoretical check on the ultimate integrated system performance.

The model is being implemented in a spreadsheet format. Such an approach allows for ease of use and immediate feedback when system parameters are changed. The major inputs fall into five major categories. The optical parameters include the primary mirror diameter, the edge taper used for the illumination of the telescope by the receiver feedhorn pattern, and the mirror surface errors. The cooling parameters consist of the amount of power dissipated on the cold plate, the relationships between radiator area and temperature, and between receiver body temperature and noise temperature. The nodding parameters of time between nods and dead time for changing nod positions determine a nodding efficiency. The source parameters include the source size and velocity width for predicting the performance on a typical source. Lastly, parametric relationships are used to define the dependence of the radiator area on aperture size, the radiator and receiver body temperatures on radiator area, and the receiver noise temperature on receiver body temperature.

SWAS PERFORMANCE MODEL ASSISTS IN MAKING SYSTEM LEVEL DESIGN DECISIONS

- Purpose of SWAS Performance Model
  - Tool for system-level analysis
  - Used for trade studies
  - Stimulate better understanding of engineering requirements
  - Provide a check on system performance

- Performance Model Approach and Input Parameters
  - Spreadsheet format
  - Optical parameters (primary mirror diameter, edge taper, surface errors)
  - Cooling parameters (power dissipated on cold plate, radiator temperature vs. area, noise temperature vs. body temperature)
  - Nodding parameters (time between nods, dead time)
  - Source parameters (size, velocity, width)
  - Relationships between primary mirror size, radiator area, radiator temperature, receiver temperature, and receiver noise temperature

The rms noise in the measured source brightness temperature after 30 minutes of observation for an assumed Gaussian source is plotted vs. the mirror diameter. For a source that does not fill the antenna beam (1 arc min FWHM) the system exhibits improved sensitivity for increasing aperture size. This is primarily due to the fact that the better spatial resolution of a larger aperture (source filling factor increases) overcomes the higher system noise that resulted from a smaller radiator in the configuration analyzed.

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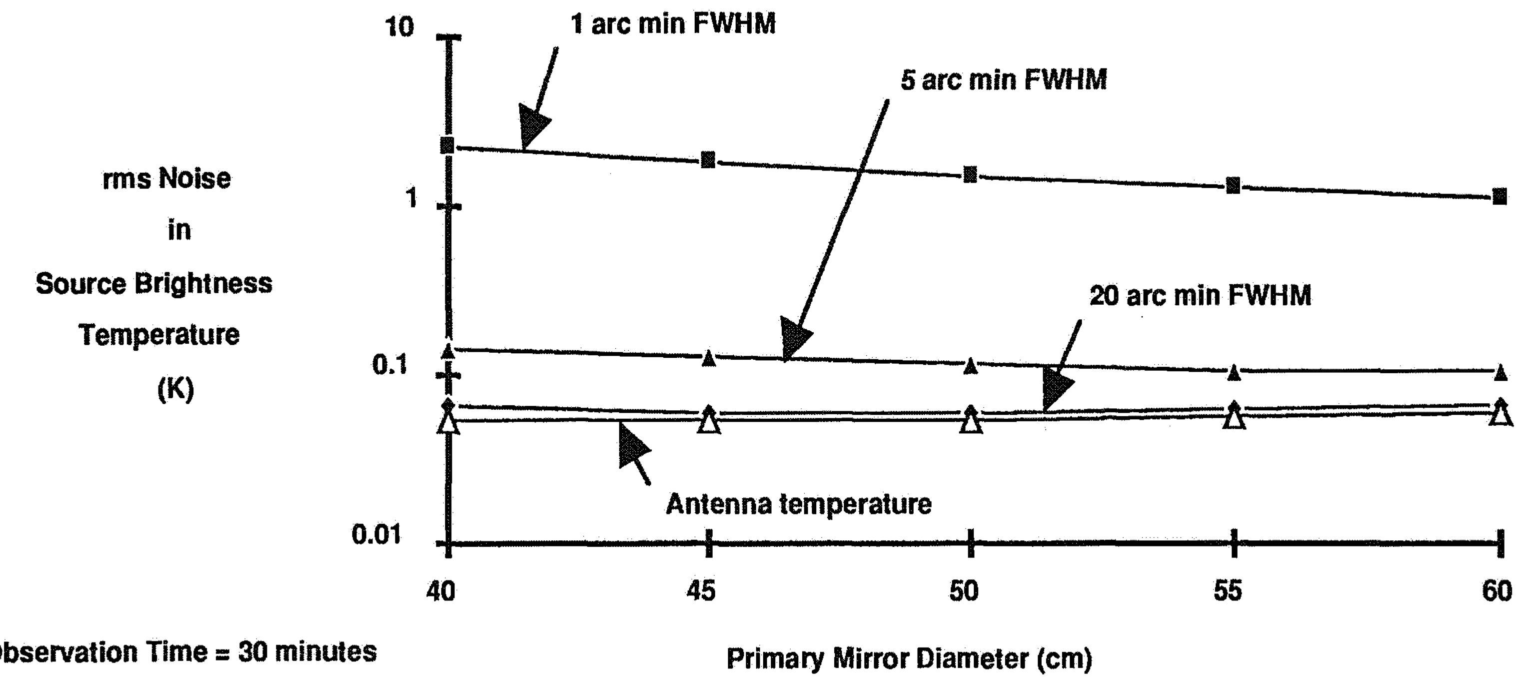
SYSTEM PERFORMANCE ON POINT SOURCES INCREASES WITH APERTURE SIZE FOR CONSTANT APERTURE AND RADIATOR AREA

rms Source Peak Brightness Temperature

vs.

Primary Mirror Diameter for Various Gaussian Source FWHMs



Observation Time = 30 minutes

Frequency = 487.25 GHz

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For extended sources, the rms noise in source brightness temperature depends weakly on primary mirror diameter. In this system model, receiver temperature varied inversely with antenna aperture, because the radiator and antenna competed for a common envelope. At small aperture sizes, the decreased signal collection dominated improved receiver noise temperature. At large apertures, the higher receiver noise temperature dominated the larger collected signal.

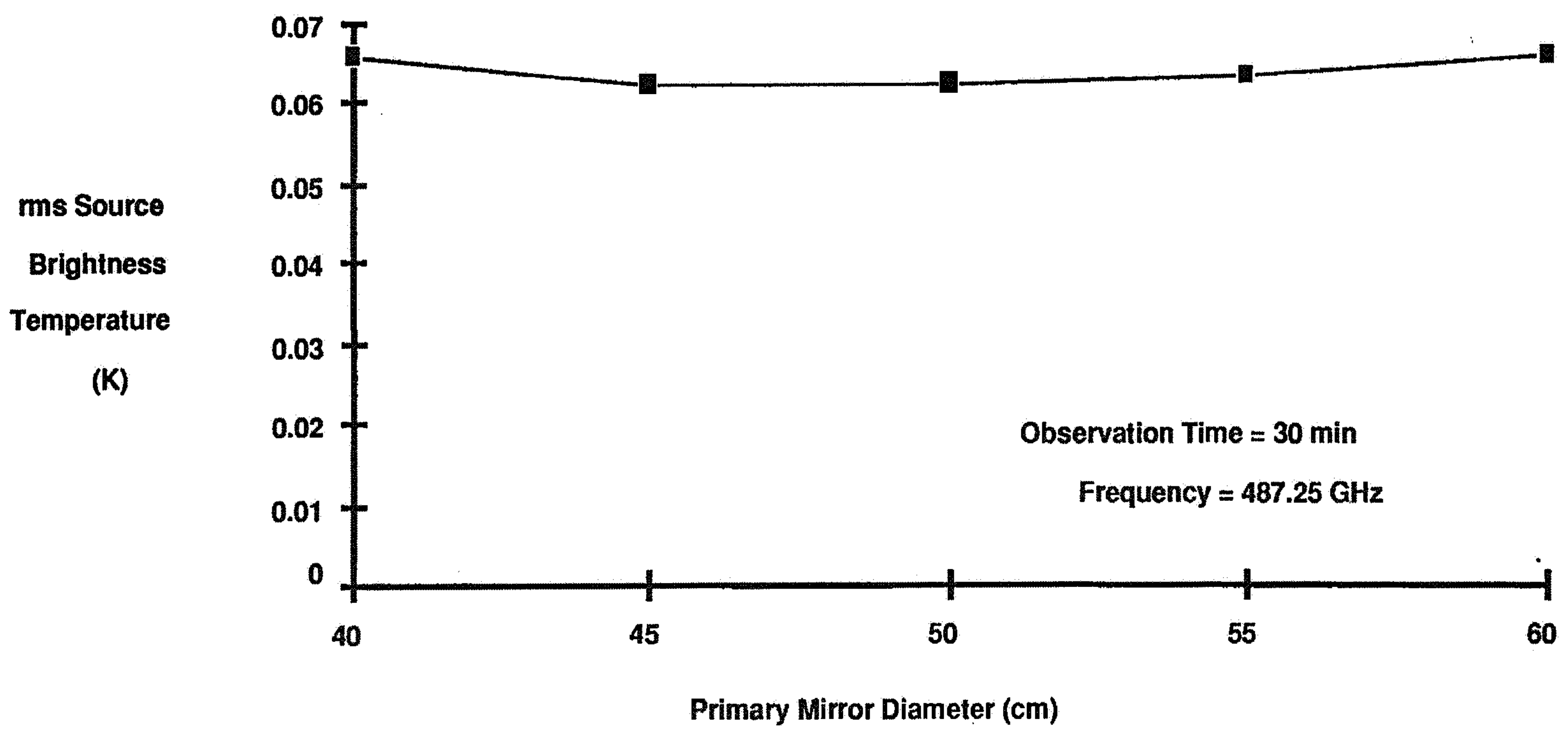
A configuration that places the radiator at an angle, allowing larger total radiator and aperture areas, is clearly preferred. The current baseline achieves this goal by giving the radiator a view of cold space both directly and in reflection off the primary mirror. The performance model will be updated after further thermal analysis.

SYSTEM PERFORMANCE ON EXTENDED SOURCES IS ONLY WEAKLY AFFECTED BY APERTURE SIZE

rms Source Brightness Temperature

vs.

Primary Mirror Diameter for 20 arc min FWHM Source



The baseline sunshade design is physically simple yet is challenging to model and analyze. Continued refinement of this design will continue throughout the extended definition and preliminary design phases.

The telescope mirrors and metering structure require challenging levels of accuracy and stability. Analysis and modeling of several candidate materials technologies will continue.

The nodding mechanisms are expected to operate over two million times during the 2-year mission. Continuing design and materials research will focus on reliably meeting this requirement.

The SWAS instrument is a study in diverse packaging requirements. We will continue to update and manipulate the CAD mechanical layout data base as more definition about sizes, cabling, and special requirements is developed.

Ball is incorporating the COBE experience into our EMI design for SWAS. Particular SWAS design features that provide EMI resistance are: exclusive use of fiber optic data bus for instrument; sensitive frequencies outside normal EMI environment; sunshade and base provide Faraday cage isolation for the receiver.

The performance model serves as our guide when making system configuration adjustments. This model will be continually updated to reflect and monitor the SWAS instrument parameters.

CONTINUED CONCEPT REFINEMENT WILL OCCUR DURING EXTENDED DEFINITION PHASE

- Analytical proving and characterization of thermal performance
- Primary mirror and telescope structure technology study
- Further definition of nodding component design
- Further coordination with Millitech, University of Cologne, and GSFC on packaging/interface definition
- Continued definition and attention to EMI considerations
- Continued updating of performance model

Telescope

Robert Brown

With a -10 dB Gaussian edge taper, the divergence to the full width at half maximum (FWHM) is 1.125 Lambda/D. The diameter required to meet the 4.9 arc min FWHM divergence is 483 mm. The Science Requirements Document also requires that the aperture must be maximized without sacrificing system sensitivity. 483 mm is the smallest collecting aperture that meets the resolution requirement, and a larger aperture is better.

In order to get an accurate baseline measurement, the line of sight of the SWAS telescope must be capable of nodding off source ±3.0 deg in two axes. The most accurate baseline measurements are obtained when spillover remains constant during the nodding precedure. For this reason, the change in spillover must be minimized. It is also important that the resolution of the off-source beam is not degraded so that a source is blurred into the beam. For a nod requirement of ±1.0 deg, 1/4 of the nod angle was the maximum blur diameter allowed. When the nod requirements was increased to ±3.0 deg, the angular blur diameter was left at 1/4 of a deg.

In order to obtain a high antenna efficiency, the wavefront error at the image of the telescope has to be less than 22-μm rms.

Off-axis designs are preferred over on-axis designs for the SWAS mission for two major reasons: first, the most sensitive portion of the feed horn pattern is the central area. Obscuring this portion would greatly lower the overall sensitivity of the SWAS instrument. Second, the near-normal surfaces of on-axis telescopes tend to reflect radiation back into the feed horn. These reflections set up standing waves and cause baseline ripple effects that reduce data quality and the calibration accuracy.

SWAS SCIENCE REQUIREMENTS DETERMINE THE TELESCOPE PERFORMANCE REQUIREMENTS

- Resolution: better than 4.9 arc min FWHM at 490 GHz
  - Requires a minimum 48-cm aperture
  - Larger aperture desired for point source observation
- Nodding: ±3.0 deg in two axes
  - Change in spillover must be minimized for accurate calibration
  - Nod accomplished in $\leq$ 4 sec
  - Off-source blur diameter to be less than 1/4 of a degree
  - Nod amplitude resolution 10 arc min
- On-source image quality: 22-μm rms wavefront error
- Configuration: Off-axis designs were emphasized to minimize standing waves and baseline ripple effects

The SWAS telescope has to be packaged, along with the sunshade, the passive thermal control system, the instrument control electronics and the spacecraft (which includes the solar arrays), within the Scout rocket payload. The area reserved for the telescope is a cylinder approximately 70 cm in diameter and 40-cm tall, leading to a compact, fast focal ratio, optical configuration.

The receiver subcontractor can fabricate submillimeter wave feedhorns that are compatible with optical systems whose geometric F-numbers are between F/2 and F/6. These limitations result from the physical sizes or efficiencies of the feedhorn waveguides for F-numbers outside this range.

The feedhorn pattern can be approximated by a Gaussian function. For the most efficient use of the telescope aperture, a -10 dB edge taper at the primary mirror is necessary.

In order to keep the receiver cold, the low-temperature components at the telescope focus should be physically located inside the instrument. Allowing these components to migrate towards the front of the instrument would increase the shading and cooling requirements of the passive thermal cooling system.

The Gaussian feedhorn pattern is not symmetrical; the ratio between the major and minor axes is approximately 1.29 and can be approximated by an ellipse. In order to maximize the aperture efficiency, an elliptical collecting aperture that matches the feedhorn pattern has been specified for the primary mirror. The receiver assembly will be assembled so that both channels have overlapping beam patterns. The addition of the reflective half-wave plate rotates the polarization of one channel so that the two receivers observe in orthogonal polarizations but with identical patterns matched to the collecting aperture.

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THE TELESCOPE/RECEIVER INTERFACE AND PACKAGING REQUIREMENTS DETERMINE MANY OF THE TELESCOPE PROPERTIES

- Fast focal ratio primary mirror is required to package telescope within the launch envelope

- System F-number: Must be >2 and <6

- Optimum edge taper: -10 dB

- Back focal distance must accommodate complex receiver
  - Calibration source and flip mirror
  - Wire grid polarizer and 1/2 wave plate
  - Two sub-millimeter wave feedhorns

- Cold receiver must be physically located inside instrument

- Matching primary mirror to elliptical feedhorn pattern maximizes antenna efficiency

- Tilting secondary mirror was rejected because of:
  - Drastic change in spillover and vignetting
  - Off-source resolution requirements not met
  - Extremely large primary mirror required

- Three mirrored systems were rejected because:
  - Concept could not be packaged within Scout shroud
  - Large mirror tilts required to meet the 3 deg nod caused internal vignetting on the secondary and tilting mirrors

- Tilting the primary mirror about its focal point met the off-source resolution requirements but was rejected because:
  - The awkward location of rotation axis resulted in high inertial moments
  - Tolerance on primary/secondary positioning is extremely tight
  - Concept requires a slightly oversized primary mirror
  - At a 3-deg nod, vignetting occurs on the secondary mirror

- Tilting the entire telescope and receiver assembly was selected as the nodding methodology because:
  - On-source resolution is maintained for all nod angles
  - Changes in spillover are minimized during nod sequence
  - Point of rotation being close to center of gravity minimizes inertial moments
  - Wide angle nod capability
  - Relative position of optical components remain fixed during the nod sequence

TILTING THE ENTIRE TELESCOPE AND RECEIVER ASSEMBLY WAS THE ONLY CONCEPT THAT SATISFIED ALL THE NODDING REQUIREMENTS

- Nodding requirements
  - High nod efficiency
  - Low power dissipation
  - Self caging for launch
  - Acceptable off-axis resolution
  - Low imparted momentum
  - Low change in spillover

- Concepts studied
  - Tilting the secondary mirror
  - Tilting a flat mirror located at the exit pupil of a Gregorian telescope (3-mirror concept)
  - Tilting the primary mirror
  - Tilting the entire spacecraft
  - Tilting the entire instrument
  - Tilting the telescope and receiver

- Concept baselined
  - Tilting the SWAS telescope and receiver

Beryllium

- Can be lightweighted
- Can be machined to required surface accuracy
- High-thermal conductivity minimizes thermal gradients
- Small thermal gradients will be amplified by high CTE

Aluminum

- Surface accuracy can be met
- A foam core construction may allow 3-kg requirement to be achieved
- Thermal distortion effects not fully characterized

Composites

- Can be lightweighted to achieve 3-kg requirement
- Low CTE will minimize thermal distortions
- Complex mandrels are required for fabrication
- Surface accuracy results in a high-precision component for this technology
- Requires a metallic coating be deposited on mirror surface

Silicon Carbide and Silicon Carbide/Aluminum Alloys

- Surface accuracy can be met
- Thermal distortion effects not fully characterized
- Can be lightweighted to achieve 3-kg requirement

DUE TO ITS POSSIBILITIES FOR LIGHTWEIGHT CONSTRUCTION AND RESISTANCE TO THERMAL DISTORTION, GRAPHITE COMPOSITES ARE THE LEADING PRIMARY MIRROR MATERIAL

- Material selection issues
  - Weight
  - Figure stability
  - Adhesion of reflective coating
  - Thermal distortion
  - Coefficient of thermal expansion

- Materials being studied
  - Beryllium
  - Aluminum
  - Silicon carbide
  - SXA (silicon carbide aluminum alloy)
  - Graphite composites

- Leading candidate
  - Graphite composites

- 55- x 71-cm collecting aperture meets the resolution requirements and matches feedhorn pattern
- Nodding capability not constrained optically by tilting the entire telescope
- System F-number (F/3.5 x F/2.7) is compatible with receiver feedhorns
- Back focal distance allows for easy integration of receiver assembly
- 1/2 wave plate allows both channels to have the same view to space
- The fast primary mirror (F/0.5 x F/0.4) allows the telescope to be packaged within the Scout shroud envelope

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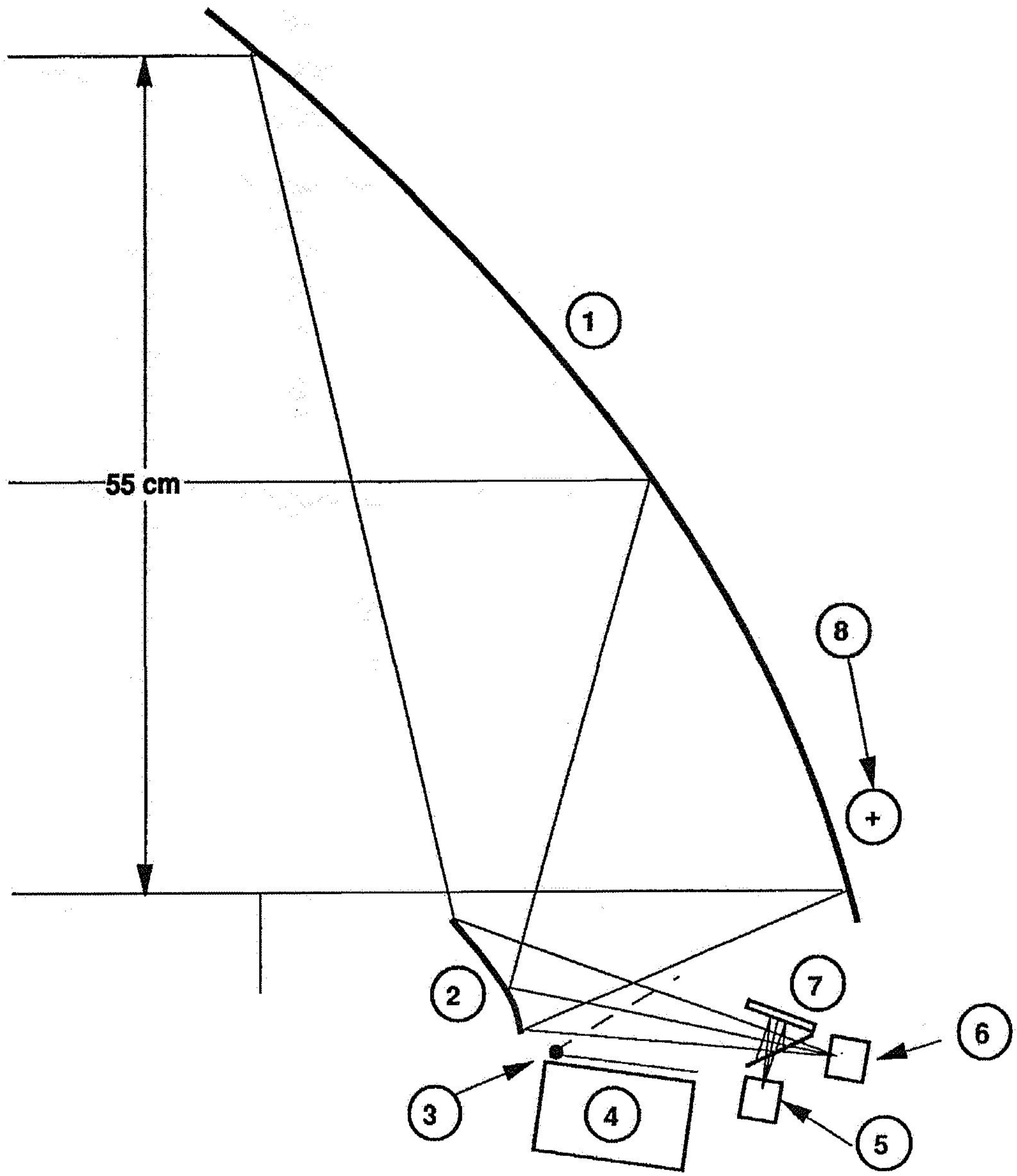
THE OFF-AXIS CASSEGRAIN TELESCOPE BASELINED FOR THE SWAS MISSION MEETS THE SCIENCE, INTERFACE AND PACKAGING REQUIREMENTS



1. Primary mirror (parabolic figure)
2. Secondary mirror (hyperbolic figure)
3. Calibration flip mirror
4. Calibration source
5. Feedhorn 1
6. Feedhorn 2
7. Polarizer grid and 1/2 wave plate assembly
8. Approximate location of rotation axis

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The wavefront errors identified are to the wavefront and not the mirror surfaces. For the primary mirror (E_P) the wavefront error of the reflected wavefront due to fabrication errors can be 18-μm rms.

E_A and E_O relate to the mechanical positioning of the primary mirror with respect to the secondary mirror. The wavefront error of 4-μm rms associated with the initial misalignment of the telescope mirrors requires that the mirror positioning must be accurate within 0.05 mm and 0.001 rad. The wavefront error of 10.5-μm rms associated with the mispositioning of the mirrors due to launch and orbit environments requires that the mirrors hold their original position to within 0.150 mm and 0.0025 rad.

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THE 22-µm rms WAVEFRONT ERROR HAS BEEN APPORTIONED TO THE ERROR SOURCES IDENTIFIED WITH THE MAJORITY GOING TO THE PRIMARY MIRROR

E = Total rms wavefront error at the feedhorn
= 22.0-µm rms

E_p = rms wavefront error introduced by the primary mirror
= 18.0-µm rms

E_s = rms wavefront error introduced by the secondary mirror
= 0.5-µm rms

E_t = rms wavefront error produced by the thermal distortion of the primary mirror
= 4.0-µm rms

E_a = rms wavefront error produced by the initial misalignment of the telescope mirrors
= 4.0-µm rms

E_m = rms wavefront error introduced by the mechanical distortion of the primary mirror by its mounting structure
= 4.0-µm rms

E_o = rms wavefront error caused by the misalignment of telescope after the initial alignment
= 10.5-µm rms

The mass goal for the primary mirror is 3.0 kg; this is a lightweight state-of-the-art mirror that will experience severe thermal cycling. Graphite composites are the most thermally stable materials capable of meeting the mass requirement. The 18-μm rms wavefront error associated with the reflected radiation requires a 9-μm rms surface accuracy. This surface accuracy is challenging for composite mirror construction.

Composite mirrors require the fabrication of a monolithic graphite mandrel, which is replicated to produce the mirror. The material for the mandrel is selected to match, as closely as possible, the coefficient of thermal expansion of the mirror material. Machining a monolithic graphite mandrel to the tolerances required for the SWAS primary mirror surface accuracy can be done but is near the limit at which the material starts to give.

The approach proposed for the development of the SWAS primary mirror represents a systematic demonstration of the technologies required to fabricate this mirror from a graphite composite material. In order to meet the surface accuracy and mass requirements, the technology development units need to be fabricated.

It is critical to the SWAS mission that the properties of the primary mirror are known as early in the development phase as possible. The other candidate materials identified can easily meet the surface accuracy requirement of the SWAS telescope. These materials may result in a significantly more massive primary mirror, and the greater thermal distortion characteristics of nongraphite materials may require increased Earth shading of the primary mirror.

PRIMARY MIRROR FABRICATION PROCESSES WILL BE DEMONSTRATED BY PROCURING TECHNOLOGY DEMONSTRATION UNITS

- Scaled technology development unit
  - Will demonstrate surface accuracy
  - Will determine expected mass properties of full-scale unit
  - Will demonstrate coating adhesion
  - Will experience thermal cycling
  - All tests can be run with existing BASG equipment
- Full-scale development prototype unit
  - Will extend processes for scaled unit to full-scale development
  - Will verify weight and surface accuracy requirements
- Flight unit and flight spare
  - Fully flight-qualified units